Using Tree-Ring Records for Understanding Droughts in a Long-Term Context:
A Guidebook

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Introduction

The purpose of this guidebook is to introduce water resource managers to extended records of streamflow and precipitation developed using tree-ring data, and to demonstrate how these data provide insights on drought risk. While streamflow and precipitation gage records show climate and hydrologic variability over the 20th and 21st centuries, the reconstructions document variability over a much longer period of time, from hundreds to thousands of years into the past.

Severe and persistent droughts have been a consistent feature of California's climate. Besides the droughts recorded in the instrumental records (Figure 1), perhaps the most remarked-upon droughts are those documented by tree stumps rooted in the bottom of what are now lakes in the Tahoe Basin. About 5000 years ago, droughts were severe and sustained enough to drain these lakes and allow the establishment and growth of trees below the current shoreline intermittently over a period of several thousand years. Additional lake-bottom stumps indicate similar conditions in the 9th and 12th centuries. These droughts occurred during a period of time called the Holocene which began approximately 10,000 years ago. The predominant natural influence on Late Holocene climate – solar radiation variability due to Earth's orbit – has changed very slowly over the last several thousand years. Consequently, the overall climate of today is in many respects not so different from the times when trees grew in the bottoms of these Tahoe area lakes. This suggests that the droughts that made the growth of these trees possible could occur today, under natural climate conditions alone, although given how rare these events are, the probability of their occurrence is extremely low.

Figure 1. Impacts of drought on Lake Oroville in 2014. From "California's Most Significant Droughts: Comparing Historical and Recent Drought Conditions" February 2016, California Department of Water Resources.

Tree rings are one of a number of sources of information on past climate and drought that also includes lake sediments, tree stumps, and historical documents. Tree rings have the advantage of being recorders of past climate on an annual timescale, precisely dated to the exact calendar year (Figure 2). This resolution and precision allow a direct calibration of tree-ring width records with instrumental climate records to develop reconstructions of past climate. Even though the tree-ring records do not extend as far back in time as some other sources of paleoclimatic data (they just overlap with most recent Lake Tahoe stump records), they provide more detailed information on droughts over the past hundreds to several thousand years than the longer records available from other sources.

Tree rings have been used to develop centuries-long reconstructions of past precipitation and streamflow that represent a much broader range of climate conditions than are contained in the modern instrumental records. The reconstructions show that 20th and 21st century droughts are not fully representative of the range of drought conditions that have occurred, and allow an assessment of modern droughts in a long-term context. Can the tree-ring records tell us if ongoing drought conditions in places like the Upper Colorado River Basin now represent the "new normal"? Tree-ring reconstructions of past climate cannot be used to predict the future, but they do tell us the range of drought conditions that have occurred in the past, and which could be expected to occur in the future under natural climate conditions. These records document the natural climate variability that will be superimposed on changes that may come about with warming temperatures in the future.

TREE RINGS AS A PROXY FOR PAST DROUGHT

The widths of annual growth rings in trees in many locations closely track variations in moisture. Because of this, tree-ring widths can be an excellent proxy for variations in moisture measured though streamflow, precipitation, and drought indices. Thus sequences of wide and narrow rings document wet and dry years for times prior to the recording of precipitation and streamflow through modern gages.

FAQ#1: How far back can you go with tree rings?

Throughout much of the semi-arid western United States, conifers with about 300 years of age are fairly common. With some searching, it is quite possible to find living trees more than 600-700 years old. Giant sequoia and bristlecone pine are especially long-lived, with oldest individuals living to 3000 and nearly 5000 years, respectively. Information from living trees can be augmented with wood from dead trees. In cool, dry locations, dead wood can be preserved on the landscape for hundreds of years, and when incorporated with data from living trees, can extend records from trees back several thousand years. The longest tree-ring records used in California streamflow and precipitation reconstructions come from foxtail and limber pine (using both living and dead trees), dating back to 783 and 340 respectively. Reconstructions depend on tree-ring data from more than just one or two sites, so the reconstructions themselves do not extend back this far.

The wide distribution of trees in highlands and mountain landscapes is fortuitous as these trees reflect moisture conditions in source regions most important to runoff and water supply.

Because tree growth is often limited by moisture in the arid and semi-arid western US, the ring-width patterns reflect variations in moisture. However, trees integrate other environmental influences into their growth rings at tree-specific to regional scales. Consequently, tree-ring records will never exactly match instrumental records from precipitation and streamflow gages. Ring-width measurements most faithfully replicate the sequences of wet and dry years, but may not fully capture the most extreme values in instrumental records (and this is more often the case for extreme wet values). Within such constraints, reconstructions from tree rings can provide plausible and conservative estimates of past hydroclimate.

DEFINING DROUGHT

Since the focus of this guidebook is on the drought information contained in tree-ring data, it is important to begin with a working definition of drought. There are many kinds of droughts, including meteorological, agricultural, hydrological, and socio-economic drought. These are primarily defined in terms of drought impacts and time frames under which those impacts occur. There are even more ways of measuring drought, from simple rainfall deficits to complex indices of drought that combine multiple climate factors.

The exact definition of drought will depend on the needs and perspectives of a user. Drought onset

Figure 2. Cross section of a ponderosa pine tree showing annual rings and their variable widths.

is often defined as the point when a metric, such as streamflow, drops below the record average, or some other threshold. After the onset, drought can be assessed in terms of duration, cumulative deficit, intensity, and/or spatial extent. Drought duration may be defined as the number of consecutive years below average, or consecutive years broken by one or more above average years. A cumulative drought deficit can be calculated over the duration of the drought. Drought intensity is sometime defined as the magnitude of the deficit on an annual basis. In addition, periods of overall dryness can be identified by evaluating precipitation or streamflow, for example, averaged over some interval of time, such as a decade.

However defined, a key feature of drought is its duration. The longer a drought persists, the greater its impacts. Persistent drought conditions can result

FAQ#2: How does the skill or confidence in drought duration (number of dry years) compare to confidence in numerical flow values?

No reconstruction will replicate a gage record perfectly, which means the reconstruction model will never explain 100% of the variance of the observed precipitation or streamflow. Typically, unexplained variance is reflected in reconstructed high and low values that are less extreme than those of the observed record. Reconstructions tend to be conservative in that regard. Reconstructions with high accuracy (that is, high explained variance) tend to be quite reliable in replicating sequences of wet and dry years, in a relative sense. Reconstructed drought duration can be sensitive to choice of threshold (mean or median) because even a small error of reconstruction in some year with precipitation or flow near the threshold can merge two short droughts or break one long drought into two shorter droughts.

in feedbacks, such as surface heating and dustiness both of which can further extend the duration of the drought. In addition, the longer a drought persists, the greater the demands are for water for both humans and natural systems. Soil drying and aquifer drawdown during droughts increase the time needed for recovery after the drought has ended.

In this guidebook we focus on drought expressed in precipitation and streamflow. These two variables are assessed on an annual time scale, defined by the water year from October-September. The threshold used to define drought is the instrumental record average. We assess droughts in two main ways: in terms of 1) duration (number of consecutive years below the average value for the instrumental record), and 2) moisture conditions averaged over specified intervals of years (5-year, 10-year and 20-year averages).

ORGANIZATION OF THE GUIDEBOOK

This guidebook first outlines the methods used to develop extended records of climate from tree rings, and to assess their skill in replicating the gage records. It then provides an overview of

reconstructions available for California and the Colorado River, with information on how to obtain these reconstructions. Links are provided to a web interface called TreeFlow, where the user can learn more about individual reconstructions available. Gage and reconstruction data can be downloaded for many locations throughout California and elsewhere in the US. The next section discusses the most severe droughts in the 20th and 21st centuries in California, and how they compare to droughts that have occurred over past centuries. Finally, the droughts contained in these centuries-long records are described, including worst-case droughts within and across basins, in northern and southern California and in the Upper Colorado River basin.

Water managers throughout the western US have used these data in a variety of ways, from simply raising an awareness of the variety of conditions that have occurred, to using the reconstructions as input into water system models. Overall, the reconstructions have provided additional insights on the droughts that may be expected in the future. We hope California water managers find this guidebook informative and useful.

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Extending the modern record of climate using tree rings

WHY LOOK INTO THE PAST?

Records of precipitation and streamflow from gages are typically less than 100 years long. While this may seem like a long interval of time, these records capture only a limited number of extreme events, such as droughts. In addition, records of this length may not contain the full range of variability that has occurred over past centuries under natural climate conditions. Instrumental records of climate and hydrology extended into the past with tree rings providing a much longer record with more occurrences of droughts and wet periods (Figure

3). These extended records can be used to place extreme events, such as the recent (2012-2016) California drought, in a long-term context. Tree-ring records can be used to address questions about a particular drought: Is the drought unprecedented in the extended record and perhaps evidence of climate change? Have droughts of similar severity occurred in the past, but so rarely that the longer record is essential to estimate their frequency? Have even more severe droughts occurred in the distant past?
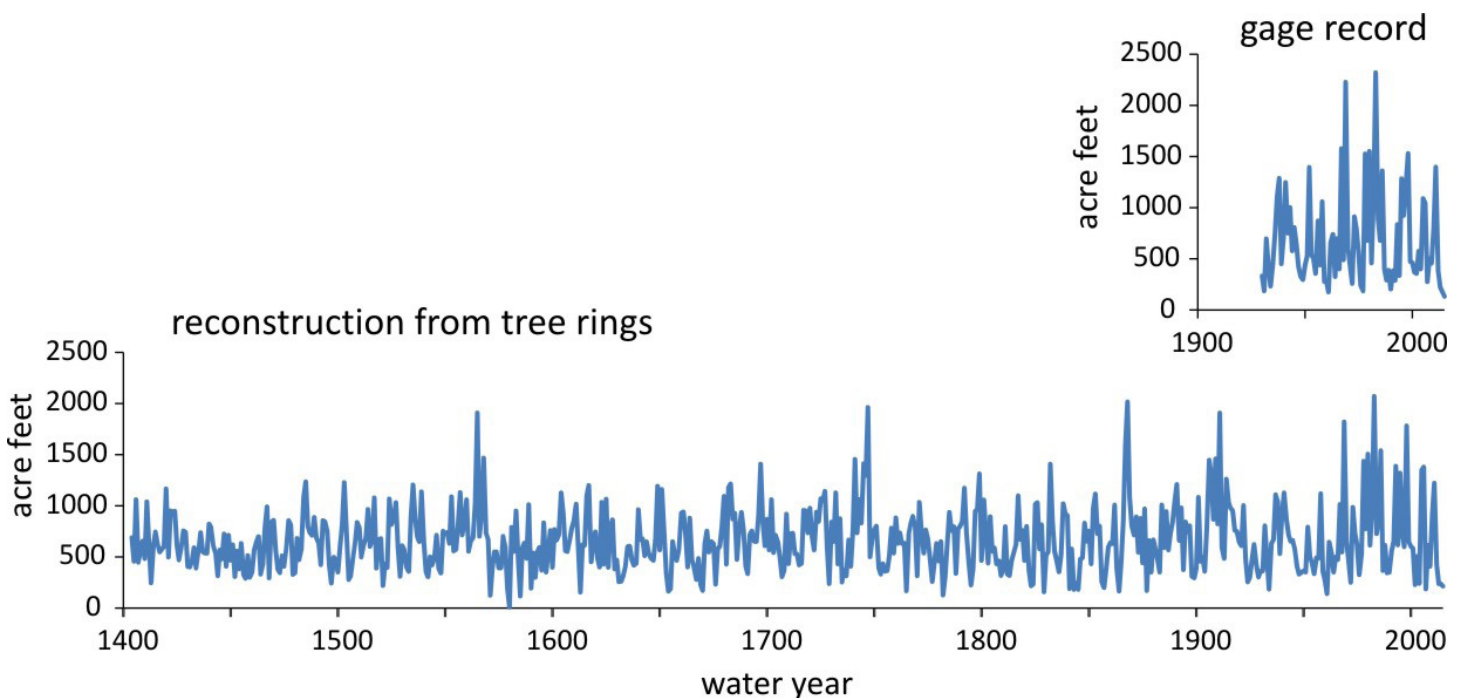

Figure 3. Graph of reconstructed Kern River streamflow, 1404-2015, compared to the much shorter gage record, 1930-2015. Note the severe drought conditions of the late 1500s.
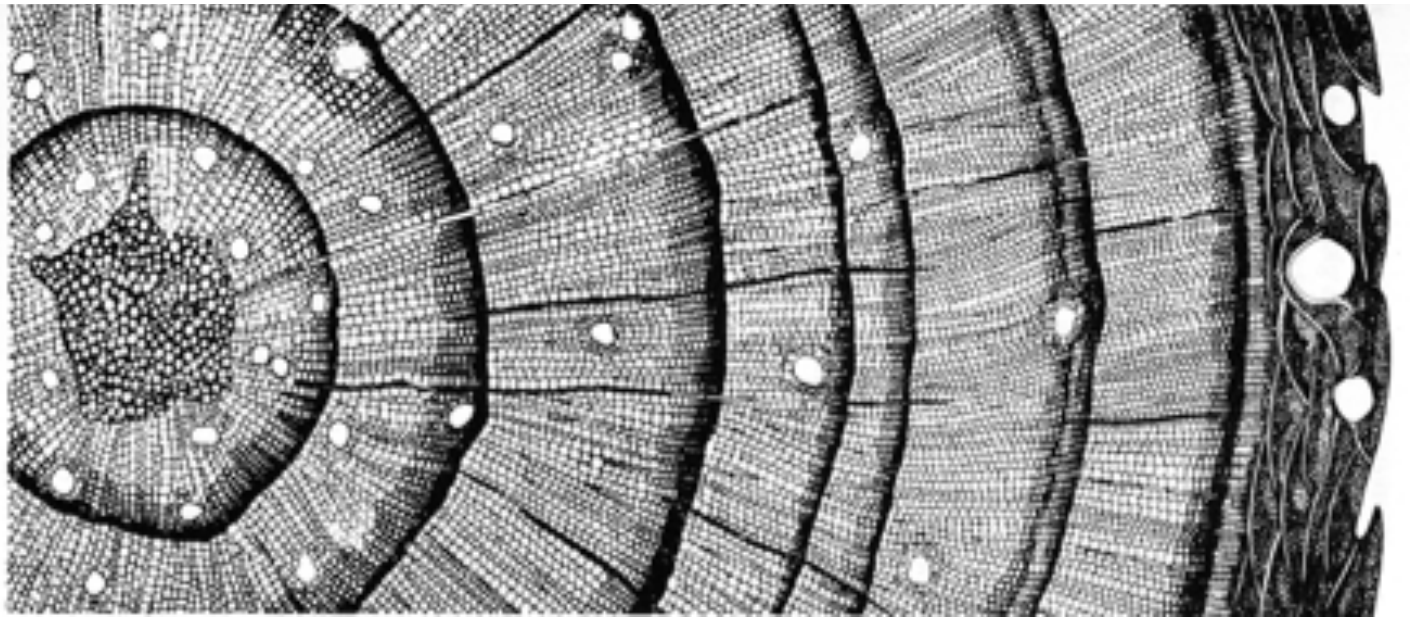
Figure 4. Illustration of a cross section of a tree adapted from Fritts 1976.

HOW TREE RINGS RECORD VARIATIONS IN CLIMATE AND HYDROLOGY

Tree rings vary in width according to the environmental factors that affect growth. In many parts of the western US, climate is the main influence on growth. In trees with growth limited by moisture availability, rings are narrow in dry years and wide in wet years (Figure 4). Trees in this part of the world grow one ring a year, and the sequence of annual ring widths forms a proxy record of climate during the life of the tree. Depending on the tree species and location, trees with useful information about past climate can live for hundreds, or in rare cases, thousands of years.

It is possible to maximize the climate information in ring widths by sampling trees from locations that are climatically stressful. For example, trees growing on steep slopes, and in shallow, rocky soil (Figure 5), are much more sensitive to variations in precipitation than trees growing in more favorable sites with rich soil and greater availability of soil moisture. Consequently, careful site selection is important when developing tree-ring records for the objective of documenting past climate variability, such as interannual variations in precipitation and temperature.

Trees directly sense variations in precipitation through soil moisture, and therefore, can be used to reconstruction past precipitation. Trees can also be used to reconstruct past streamflow, but the relationship between tree growth and streamflow is less direct than the relationship between tree growth and precipitation. Streamflow reconstruction generally relies on trees sampled from dry upland slopes, as described above. These trees reflect the overall soil moisture conditions in a basin. The soil moisture, influenced primarily by cool season precipitation along with melting snow, is a major contribution to annual runoff (Figure 6). In contrast, trees growing in close proximity to river channels and in flood plains typically receive plenty of moisture for growth. Ring widths from such trees may not vary much from year to year, and consequently, they do not strongly reflect variations in moisture.

The water year (October-September), over which "annual" streamflow is generally assessed, also happens to be a good approximation of the time frame of the climate influencing annual growth rings. Fall moisture, winter snowpack, and precipitation and evapotranspiration in the spring and summer all contribute to both total water year flow and total ring width. Although the relationship between ring widths and streamflow is less direct that the relationship between ring widths and precipitation, as explained above, ring width is often more highly correlated with streamflow than with precipitation. The reason for this lies with the fact that streamflow, like tree-growth, integrates the influence of both precipitation and evapotranspiration over the course of the water year. It is this integration of climate in the measure of water year streamflow that is similarly replicated in the annual ring width of a tree.

DENDROCHRONOLOGY FIELD AND LAB METHODS

Dendrochronology is the science that deals with the dating and study of annual growth rings in trees. This discipline has established methods for extracting useful climate information from trees. In order to obtain the best information from tree rings for reconstructing precipitation and streamflow, specific tree species and types of sites are targeted for sampling. As mentioned above, sites with stressful climate conditions will ensure trees are sensitive to climate variability (e.g., precipitation). California is fortunate in having several tree species known to be particularly sensitive to variations in moisture. These include bigcone Douglas-fir, ponderosa pine, Jeffrey pine, foxtail pine, and blue oak (Figures 7 and 8). Along with site characteristics and tree species, the other key attribute targeted for in sampling is age.

Figure 5. Old Douglas-fir tree growing on steep, rocky slope in the Upper Colorado River basin.
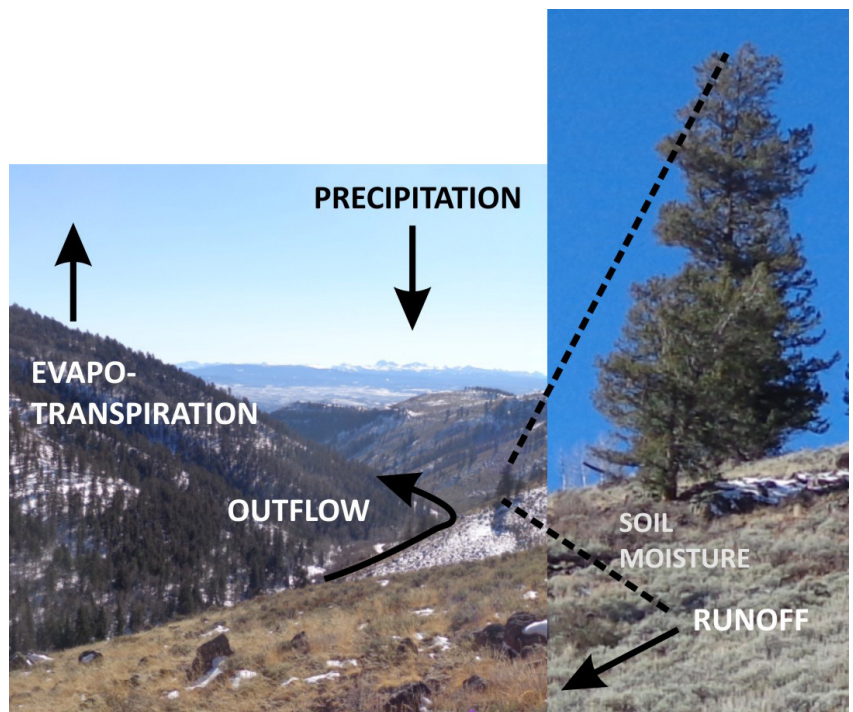

Figure 6. The relationship between tree ring-widths and streamflow is indirect but robust. Similar to an annual ring, annual (water year) streamflow integrates the effects of precipitation and evapotranspiration as mediated by the soil, over the course of the year.

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Old trees are identified not just by large size (which is often not the best indicator of age), but by features such as heavy upper limbs, thick bark, twisted trunks, spike tops, and a gnarled appearance.

Once an appropriate site has been identified, approximated 20-30 trees are targeted for sampling with an increment borer. An increment borer is a

Figure 7. Foxtail pines near Guyot Pass, Pacific Crest Trail, Sierra Nevada, CA

hollow shaft of steel with threads and a sharpened bit on one end and a handle on the other. After the increment borer is drilled into the tree, a curved extractor, or "spoon" is inserted into the shaft to extract the core (Figure 9). Two cores per tree are extracted, assigned identification numbers, and stored in paper straws for transport back to the lab. At some sites, stumps, standing dead trees or wood lying on the ground may be sampled with a chainsaw. In cool, arid climates, such wood can be preserved on the landscape for centuries, and can be used to extend the living tree records back in time.

Back at the laboratory, cores are mounted into wooden core mounts and sanded with progressively finer grits of sandpaper to achieve a fine finish.

Figure 8. Bigcone Douglas-fir near Hard Luck Campground, Los Padres National Forest, CA (photo credit, Cedar Welsh)

Figure 9. Top: Dendrochronologist coring a tree with an increment borer. Lower left, increment borer bit. Lower right, core extracted from the tree.

Cross sections are likewise sanded (Figure 10). This finish allows dendrochronologists to clearly see ring boundaries and cellular structures under magnification, even tiny rings that are only a few cells wide ("micro" rings).

One of the most important steps in the laboratory is assigning exact calendar dates to each and every ring. This process, called crossdating, is the foundation of dendrochronology. When cored, the current year of growth is the ring next to the bark. But instead of just counting backward in time from this ring, crossdating matches the patterns of ring widths among trees at a site. Tree growth is influenced by a common regional climate signal, and the pattern of wide and narrow rings is highly replicated between trees within a site and between nearby sites (Figure 11). The pattern matching ensures that extremely small "micro" rings or locally absent rings are accounted for, and that other ring anomalies do not cause miscounts. Crossdating also enables the determination of the dates of rings in wood from dead trees, as long as their tree rings overlap in time with the record from living trees.

Figure 10. Collection of sanded cross sections of dead wood from the Upper Colorado River basin.

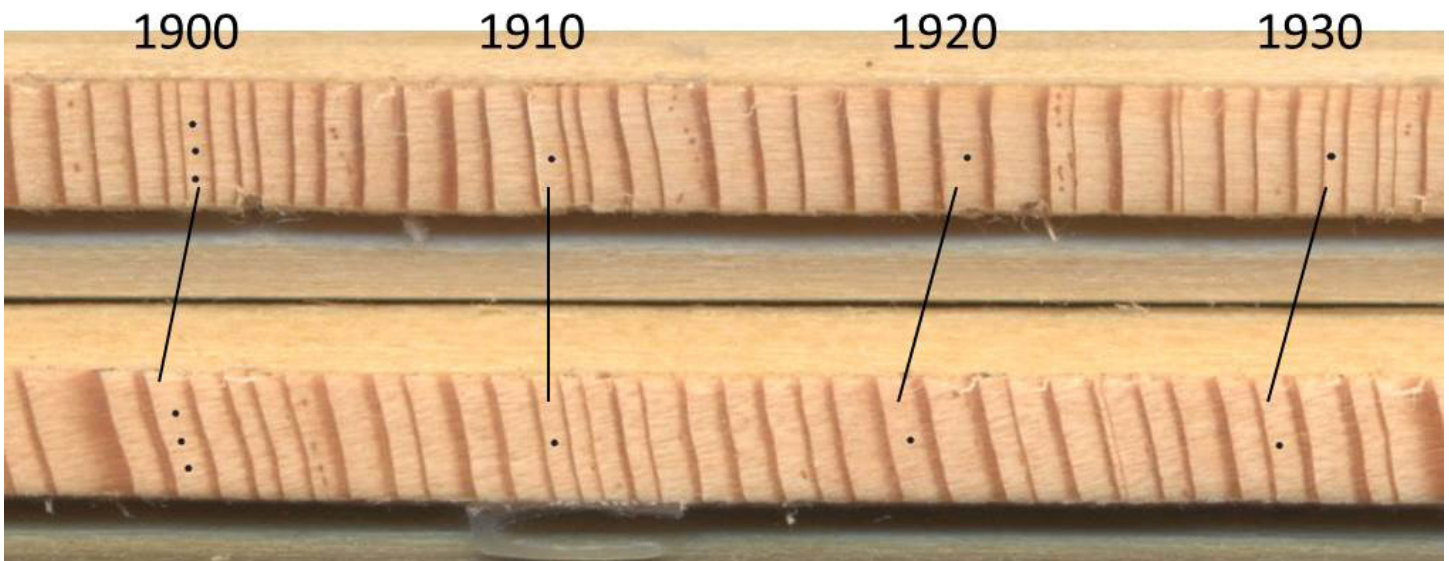Figure 12. Computer-assisted tree-ring measuring system with microscope.

Figure 11. Cores from two different trees illustrating crossdating using pattern matching of ring widths.

The ring widths of each dated sample are measured using a computer–assisted sliding stage system (Figure 12), and the measurements are digitally recorded to thousandths of a millimeter. Each ring width measurement series is detrended to remove a decreasing trend related to the geometry of the tree (i.e., rings tend to be wider in the center of the tree), then all of the series for a site are averaged together to create a site tree-ring chronology. By combining measurements from multiple trees at a site, the common information – related to climate – is emphasized, while the tree-specific variations are minimized (Figure 13). The site tree-ring chronology is the basic time series used to reconstruct past climate and hydrology.

USING TREE-RING DATA TO RECONSTRUCT STREAMFLOW

Tree-ring reconstructions of past climate or hydrology are developed by calibrating tree-ring chronologies with an instrumental record to estimate past conditions. A statistical model is used in which tree-ring chronologies from multiple sites are the predictors of climate or streamflow. The simple schematic in Figure 14 shows the basic steps in a reconstruction process.
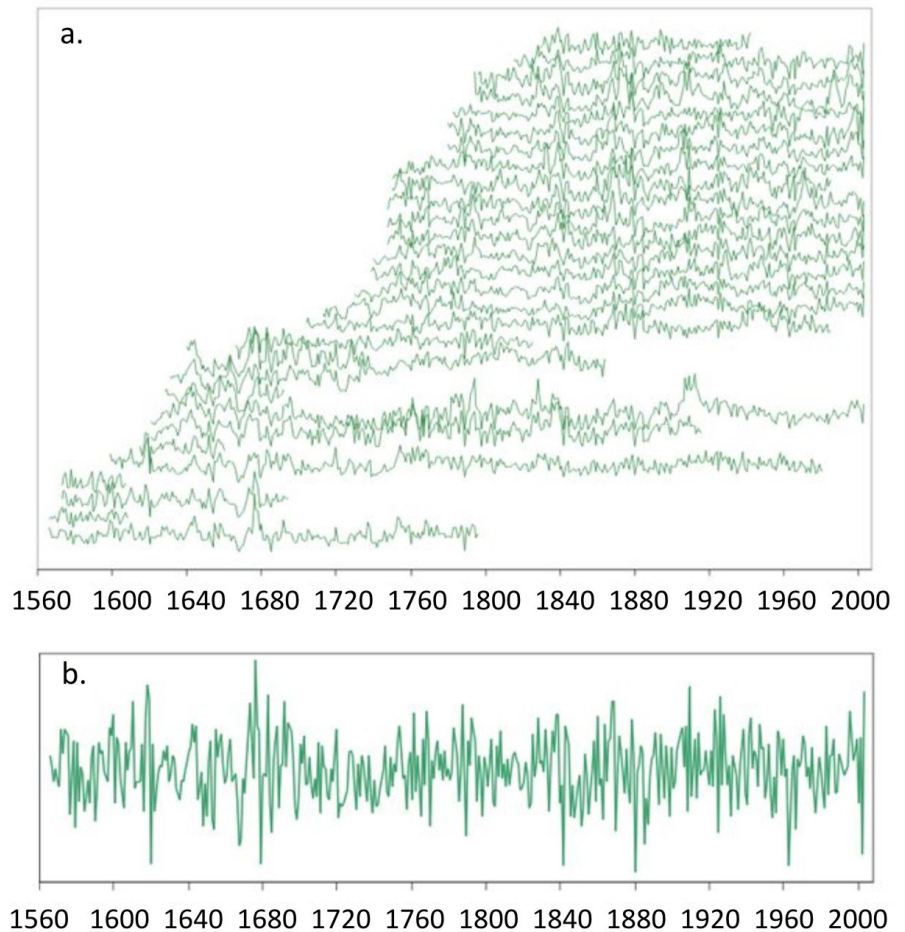

Figure 13. a. Time series of ring widths from all tree sampled in a site (series have been detrended to remove size-related trend). b. The average of the samples, resulting in a site tree-ring chronology.

Requirements for the observed streamflow or climate record include a gage record that is:

- Long enough to provide a continuous record of at least 30 years of overlap with the tree-ring records
- Either a natural flow record or a gage record that has been corrected for depletions, diversions and other human impacts (for streamflow)
- Of good quality (e.g., measuring methods or instrumentation have not changed, the recording stations has not moved)

Site tree-ring chronologies are calibrated with the observed climate or hydrologic record for which a reconstruction is desired to develop a statistical model. The process for statistical calibration is most commonly a regression-based model, in which single tree-ring chronologies or sets of chronologies are used to predict or estimate a climate variable such as total winter precipitation or water year streamflow. Other statistical approaches can and have been used as well.

Once a model is generated, the output is assessed to ensure that it meets the assumptions of the statistical method used. The reconstructed precipitation or streamflow values for the period of calibration are compared to the observed values to evaluate the accuracy of the reconstruction in replicating the characteristics of the gage record. The model is also validated by comparing predicted values with observed values for years or portions of the gage record withheld from the calibration. "Skill" is the ability of the model predictions to replicate data not used in calibration of the model. High skill lends confidence to the prediction or reconstructions from the model. If judged satisfactory, the model is finally applied to the full period of time encompassed by the tree-ring chronologies to develop the full reconstruction.
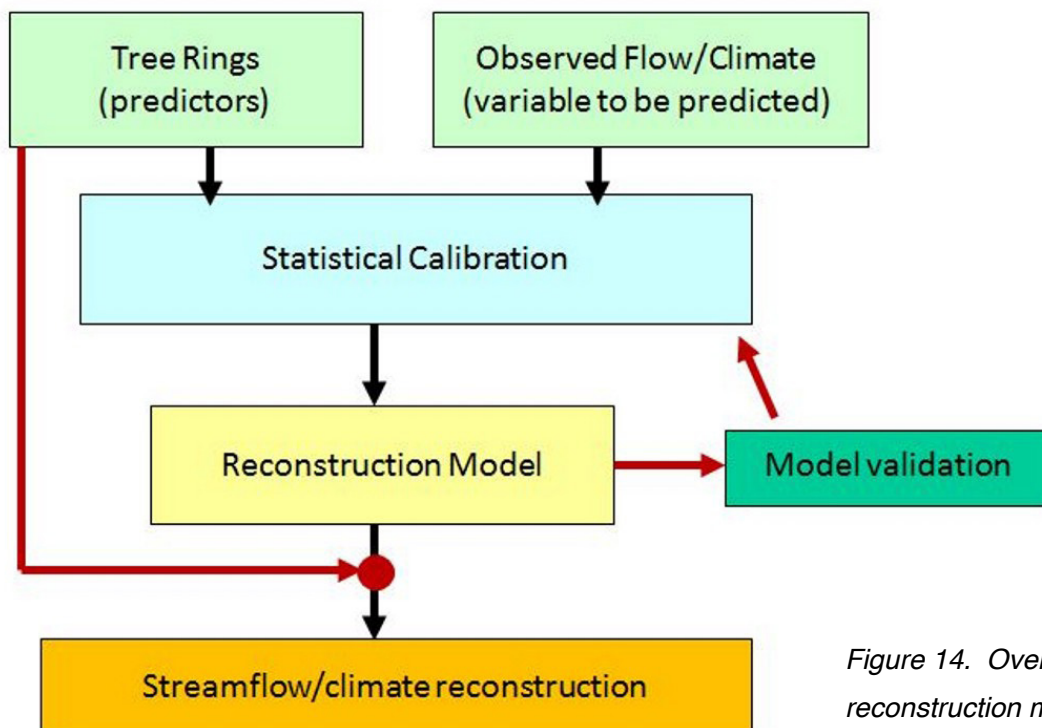

Figure 14. Overview of reconstruction methodology.

It is important to keep in mind that no reconstruction will replicate a gage record perfectly. That is, the reconstruction model will never explain 100% of the variance of the observed precipitation or streamflow. The unexplained variance is considered "model uncertainty," and can be summarized by confidence intervals as shown in Figure 15. The wider the confidence intervals, the greater the uncertainty in the reconstructed values. In the full reconstruction, before the start of the calibration period, the 95% confidence interval is the zone within which the true (unknown) precipitation or streamflow lies with 95% certainty.

Besides the uncertainties related to the reconstruction model, there are other sources of uncertainty. There is no one "correct" way to develop a reconstruction. A number of choices are made along the way, including the data treatment in developing chronologies, the chronologies to be included in the pool of potential predictors, and the criteria for selection of predictors from the pool. These choices can result in slight differences in the final reconstruction. It is useful to acknowledge that gage records themselves also have uncertainty, and that the reconstruction quality relies on the quality of the observed record. Specifically, the flow of most western US rivers, except those high in the headwaters, has been highly impacted by diversions, depletions, and/or reservoir operations. Consequently, records of estimated natural flow are needed for developing reconstruction models. These estimates are based on the best available, but invariably incomplete, information on water use over the 20th and 21st centuries. Since 1) trees are imperfect recorders of climate and hydrology, 2) observed records can have errors, and 3) slightly different modeling choices can impact the final reconstruction, it is prudent to consider a reconstruction a plausible estimate of past climate or streamflow, and a conservative one at that.
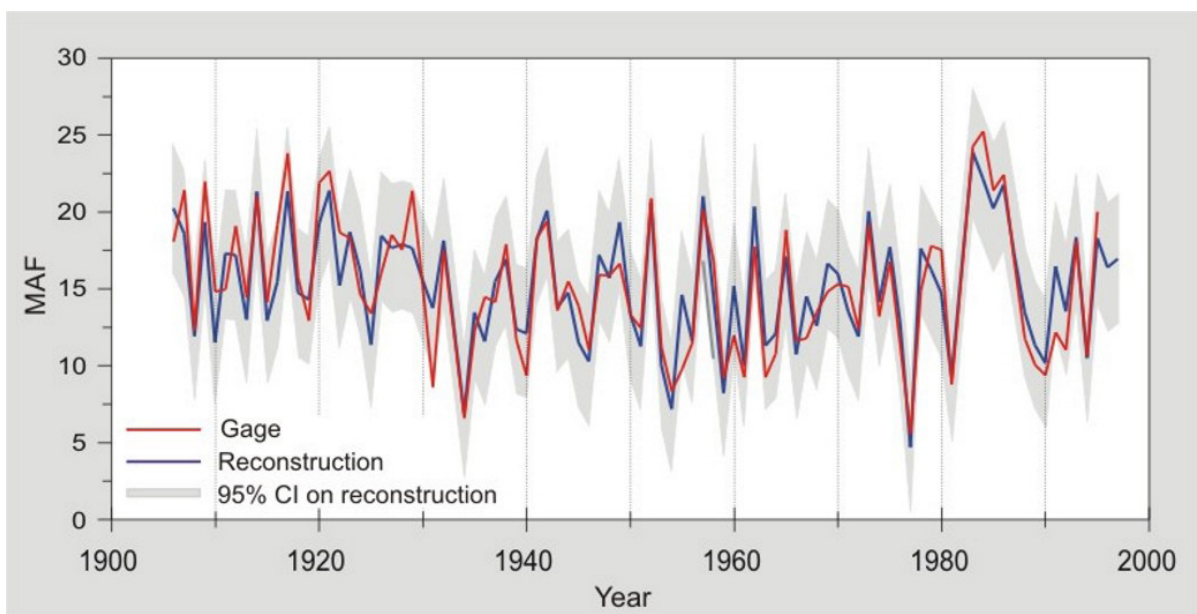

Figure 15. Gage record in red, compared to reconstruction of streamflow in blue, with the 95% confidence interval for the reconstruction. The gray band highlights the range of values for which there is a 95% probability that the gaged flow values will fall.

3

Tree-ring reconstructions of precipitation and streamflow in California

In California, the main runoff-producing parts of the state are in the north, while the largest proportion of the population is in the south, and main agricultural areas are in the central and southern parts of the state. The most important sources of surface water for much of the state are the Sacramento and San Joaquin River watersheds, and infrastructure has been developed to convey these water resources to the south via the State Water Project's California Aqueduct. Southern California has municipal and industrial water needs, along with significant agricultural water use that result in a demand for water that far exceeds the supply from local sources. Consequently, southern California relies on three major surface water sources from outside the region. Surface water is delivered from northern California via the California Aqueduct, and from the Owens River and Mono Lake via the City of Los Angeles Aqueduct. The third major source is imported water from the Colorado River basin, conveyed to southern California via the Colorado River Aqueduct. Local water comes primarily from groundwater.

Tree-ring based reconstructions of streamflow and precipitation have been generated for a variety of these source regions for California water supplies (Figure 16). Reconstructions are available for the following regions:

Sacramento River watershed:
- Sacramento River above Bend Bridge
- Feather River inflow to Lake Oroville
- American River inflow to Lake Folsom
- Yuba River at Smartville
- Sacramento River index

Klamath watershed (not in California, but water resources are diverted into California):
- Klamath River at Keno
- Trinity River at Lewiston

San Joaquin River watershed:
- San Joaquin River at Millerton
- Stanislaus River inflow to New Melones Lake
- Tuolumne River inflow to New Don Pedro Reservoir
- Merced River inflow to Lake McClure
- San Joaquin River index

Southern California/Sierra Nevada watersheds:
- Arroyo Seco, near Pasadena, in the Los Angeles River basin
- Santa Ana River near Mentone
- Kern River below Lake Isabella, draining the southern Sierra Nevada

Southern California (water year precipitation):
- Ojai, in the coastal region near Santa Barbara
- San Gabriel Dam, in the San Gabriel River basin
- Lake Arrowhead, near the Mojave River headwaters
- Cuyamaca, east of San Diego

The northern and central California reconstructions include many of the sub-basins of the Sacramento/ San Joaquin region, as well as the Klamath and Trinity Rivers that contribute, via diversion, to the Sacramento River. The southern California reconstructions are regionally representative of the sub-regions within this area, and for the South Coast hydrologic region in particular. The set of gages targeted for reconstruction was selected based on

1) the availability of estimated natural flow records and high-quality precipitation records, which were 2) spatially distributed and 3) long enough to have an adequate overlap in time for the calibration of reconstruction models. The information in these California reconstructions is also applicable to nearby areas that are under the influence of same region-wide climate controls.
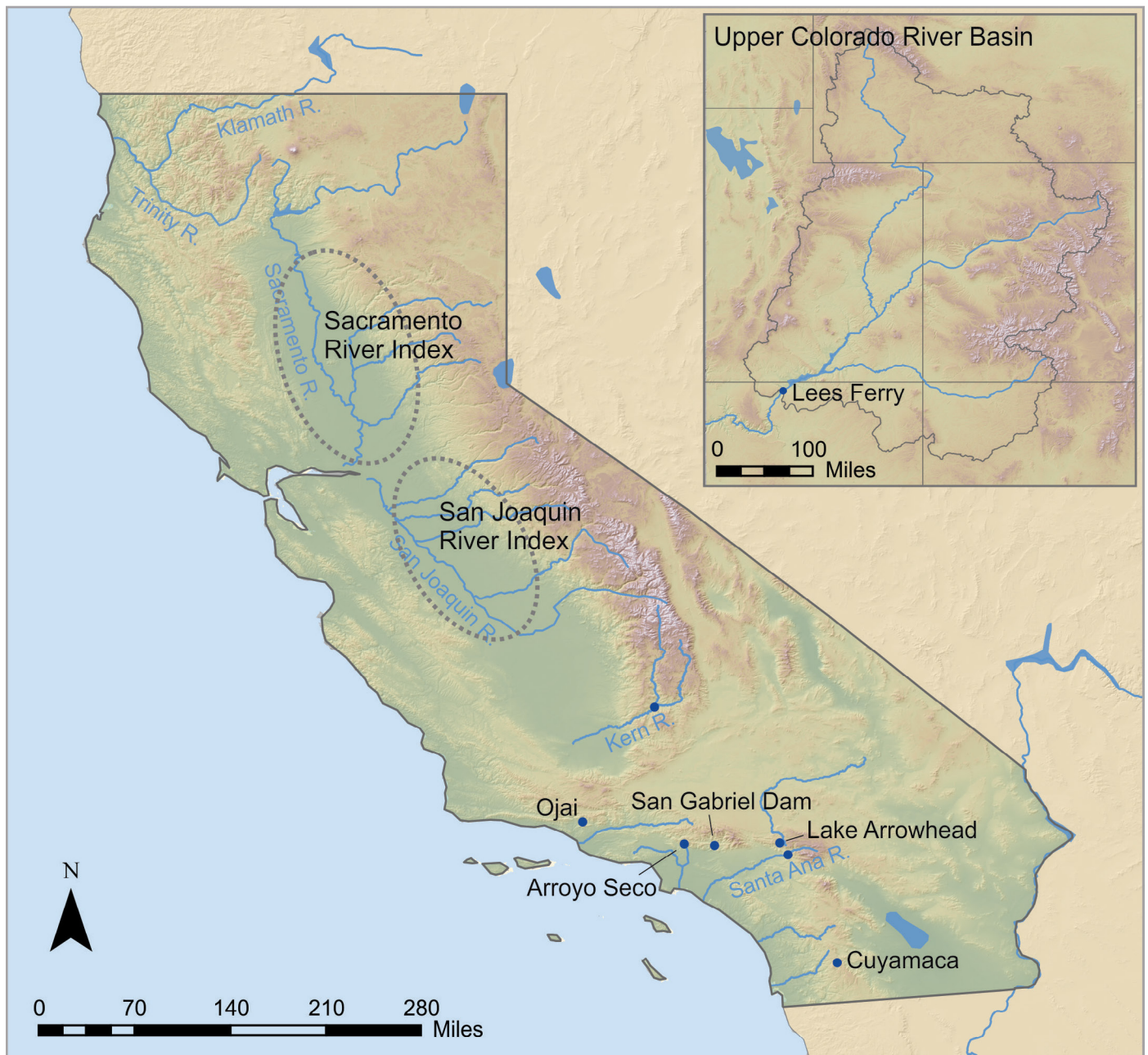

Figure 16. Locations of rivers trend gages for which California streamflow and precipitation reconstructions have been generated, along with the Colorado River at Lees Ferry flow reconstruction.

OBTAINING RECONSTRUCTIONS: A TREEFLOW PRIMER

Reconstructions for the gages and locations listed above can be obtained from the TreeFlow web site for California, [http://www.treeflow.info/california]. The TreeFlow web resource was initially developed to host reconstructions of streamflow in support of water resource management, although the data it provides serves many other uses. The reconstructions are available via a clickable map (Basin Map) or table (Reconstructions) on the California TreeFlow web site. Identifying and clicking on a gage of interest from either the table or the map takes the user to that gage's web page. Reconstructions for other gages of relevance to California water supplies can be found on other basin pages (i.e., Upper Colorado River basin).

An example web page for the gage at San Gabriel Dam for water year precipitation is provided below (Figure 17). Across the top of the page are quick links to metadata, information on the reconstruction skill (model calibration and validation statistics), graphics that compare the observed and reconstructed data, and a link to the actual data files (both observed and reconstructed data are provided). Underneath the banner is a short paragraph providing some background on the reconstruction.

There are two versions of each southern California reconstruction. One reconstruction is based on a reconstruction model that incorporates more chronologies and has the most skill in replicating the observed gage series (called "most skillful"). The other necessarily relies on fewer, older chronologies and places a greater importance on the length of reconstruction. This second version (called "longest") extends as far in time as possible, trading off some skill for length.

San Gabriel Dam

Metadata | **Calibration & Validation** | **Most Skillful Reconstruction** | **Longest Reconstruction** | **Data File**

Background

The San Gabriel Dam impounds the San Gabriel River, which has its headwaters in the San Gabriel Mountains, with peaks up to 10,000 feet. The precipitation gage at San Gabriel Dam generally reflects the upper portion of the San Gabriel River basin. The precipitation data, for the years 1938-2015, were obtained from the Los Angeles County Department of Public Works.

The reconstruction of water year streamflow at San Gabriel Dam was generated as part of a project supported by the California Department of Water Resources (CADWR). This project includes reconstructions of water year precipitation (San Gabriel Dam, Lake Arrowhead, Ojai, and Cuyamaca) and streamflow (Arroyo Seco and Santa Ana River) for southern California and the Kern River in the southern Sierras. This set of reconstructions was developed by Dave Meko, Erica Bigio, and Connie Woodhouse in 2017, based on updated and new collections of tree-ring data in California sampled for this project.

Figure 17. Sample TreeFlow web page for the San Gabriel Dam precipitation reconstruction.

Both versions of the reconstructions are shown in the following two tables. The metadata table contains information about the observed record used for the reconstruction model calibration, along with information about the length of the observed and reconstructed records and some basic statistics (mean, median, minimum, and maximum values) for the observed and reconstructed series (Figure 18). The second table compares the calibration and verification measures for the two reconstructions (Figure 19).

The **Calibration Statistics** are used to evaluate the ability of the tree-ring reconstruction model to replicate the values in the observed record (precipitation or streamflow) used in the reconstruction model.

Metadata

Observed Record	Observed Precipitation	Reconstructed Precipitation: Most Skillful Model	Reconstructed Precipitation: Longest Model
Location: San Gabriel Dam, CA (station ID 425B)	**Period: 1938-2015**	**Period: 1405-2016**	**Period: 1126-2015**
Source: Los Angeles County Department of Public Works, Water Resources Division.	Mean precip: 28.27 in. Median precip: 22.71 in. Minimum: 10.62 in. Maximum: 72.36 in.	Mean precip: 27.87 in. Median precip: 26.95 in. Minimum: 8.27 in. Maximum: 67.21 in.	Mean precip: 28.11 in. Median precip: 24.48 in. Minimum: 8.57 in. Maximum: 68.24 in.
Adjustment: none			

Figure 18. *Example of metadata table for the San Gabriel Dam precipitation reconstructions.*

Figure 19. *Example calibration and verification statistics for the two reconstruction of San Gabriel Dam precipitation.*

Statistic	Most Skillful: Calibration	Most Skillful: Validation	Longest Model: Calibration	Longest Model: Validation
Explained variance (R2)	0.77		0.60	
Reduction of Error (RE)		0.78		0.57
Standard Error of the Estimate	6.677 in.		9.368 in.	
Root Mean Square Error (RMSE)		6.970 in.		9.839 in.

These statistics include the **Explained Variance (R²)** and the **Standard Error of the Estimate (SEE)**. If a model has no skill whatsoever, R^2 values will be close to zero, while a model that exactly replicates the observed values would explain 100% of the variance (and is not expected). Typically, a relatively skillful reconstruction explains 60-80% of the variability in the instrumental record. The SEE is a measure of the difference (sometimes called the error or uncertainty) between the observed and reconstructed values. The SEE value represents the average difference for all the years in the calibration period.

The **Validation Statistics** assess the skill of the reconstruction model to estimate values that are not included in the calibration of the model. These statistics include the **Reduction of Error (RE)** and the **Root Mean Square Error (RMSE)**. The RE is used to assess the skill of the reconstruction model compared to a reconstruction model consisting of the mean value of the calibration period (i.e., a "model" that has no knowledge, with the mean value for each year). A reconstruction with an RE value similar to the R^2 value is considered highly skillful. RMSE is similar to the SEE in that it measures the difference between observed and reconstructed values, but in this case, for the values that were not included in the calibration of the model. For more details on these statistical measures, see the box below.

As shown in the example tables for the San Gabriel precipitation, the most skillful model, which starts in 1405, explains 77% of the variance in the observed

More Details on the Calibration/Verification Statistics

Explained Variance (R²): A measure of the proportion of total variation about the mean in the predictand (observed flow or climate record) that is explained by the tree-ring regression model.

Standard Error of the Estimate (SEE): The square root of the mean square of the calibration errors (observed flow minus estimated flow). In other words, the SEE is a measure of the spread of the calibration errors and is indicative of the typical size of error in the units of the predicted variable.

Reduction of error (RE): A measure of the skill of the reconstruction model, or the ability of the model to predict observations of the predictand (precipitation or streamflow) not used in calibration of the model. RE is the validation equivalent of the explained variance of calibration (R^2). A model with RE>0 is considered to have "some" skill, while a model with RE nearly as high as R^2 is considered to be strongly validated.

Root Mean Square Error (RMSE): A measure of the spread of the validation errors (observed flow minus estimated flow). RMSE is the validation equivalent of the calibration statistic SEE. RMSE is always greater than SEE, but for a robust model, RMSE should be similar in magnitude to SEE. This indicates that the typical error of validation is not much larger than the typical error of calibration.

FAQ#3: Where can I get more reconstructions?

All of the reconstructions in this guidebook, along with reconstructions developed previously, are available on the TreeFlow website (www.treeflow.org), and for California in particular, from California TreeFlow (http://www.treeflow.info/california). As described in this guidebook, this website is a publicly-available repository for tree-ring reconstructions of streamflow for California and elsewhere in the US. At a few locations, mainly in southern California, precipitation reconstructions are also available.

record, while the longest model, which starts in 1126, explains slightly less variance (60%). RE is similar for both models, but slightly lower than R^2. The Standard Error of the Estimate (SEE) of the most skillful model is about 7 inches. SEE is a practical statistic in that it measures the typical error of reconstruction, or the absolute difference of observed and reconstructed water year precipitation. This difference is similar for the verification data, but a bit greater for the longer, less skillful model.

Below the tables is a set of three graphs for each of the reconstructions. The first is a scatter plot, which shows the relationship between the reconstructed and observed values. For a perfect one-to-one relationship, the dots would line up along the diagonal straight line (x=y). The closer the dots are to the line, the more accurate the reconstruction in replicating the observed values. The scatter plot for San Gabriel Dam precipitation suggests that lower precipitation values are more closely matched than high precipitation values by the reconstruction (Figure 20). There are fewer very wet years, but the error is relatively large in those years.
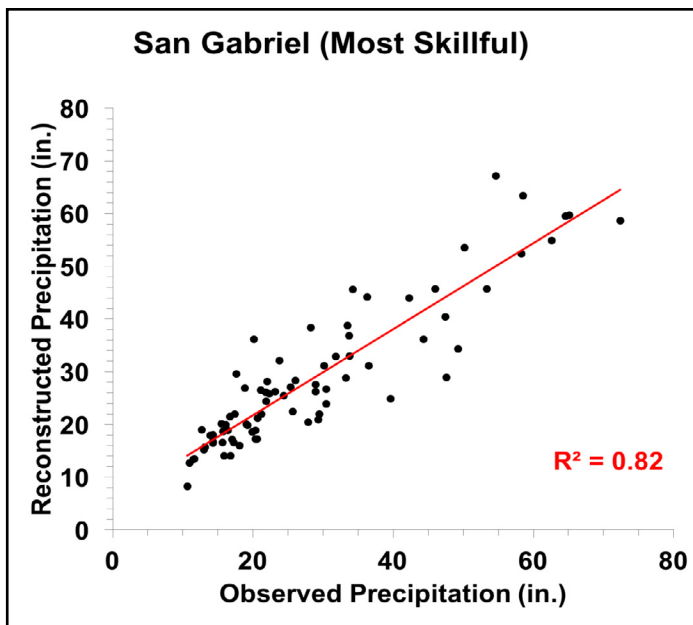
The second graph is a time series of the observed (gray line) and reconstructed (blue line) annual values. This graph shows how close the reconstruction tracks the observed values in each year. In the graph for San Gabriel Dam precipitation (Figure 21), the reconstructed values often do not quite match the very wettest observed values, but they do a very good job of replicating most of the driest years.

Figure 20. Scatter plot of reconstructed precipitation versus observed precipitation for the gage at San Gabriel Dam.
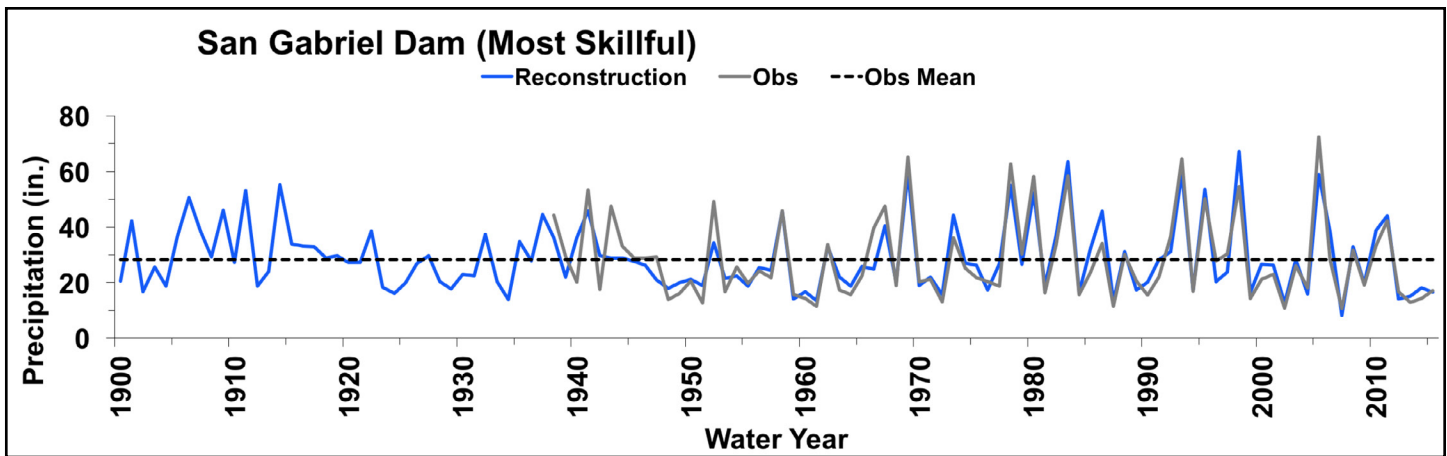
Figure 21. Time series plots of observed and reconstructed values for the San Gabriel precipitation reconstruction.

The third and fourth graphs show the full "most skillful" reconstruction, along with the much shorter observed record (Figure 22). These graphs underscore the time extension provided by the reconstruction, and illustrate how features in the observed record compare with those in the full record. This comparison is facilitated in the fourth graph (Figure 22, bottom panel), in which values are smoothed to emphasize multi-year variability. For example, the smoothed data highlight the extended drought conditions in the mid-1400s and show that this drought was longer but less severe than a drought in the mid-20th century.

On the San Gabriel Dam precipitation web page, three additional graphics show the reconstruction results for the "longest" reconstruction.

TREE-RING DATA FOR CALIFORNIA

The California TreeFlow website also contains a page (http://www.treeflow.info/california) that shows the locations and names of existing tree-ring chronologies from moisture-limited trees in California and surrounding areas. A subset of these chronologies has been used for the streamflow and precipitation reconstructions described in this guide. The tree-ring chronology data can be found and downloaded from the International Tree-Ring Data Bank, hosted by the NOAA Paleoclimatology program (https://www.ncdc.noaa.gov/paleo-search/). Hyperlinks to each chronology are embedded in a clickable map of tree-ring chronology locations.
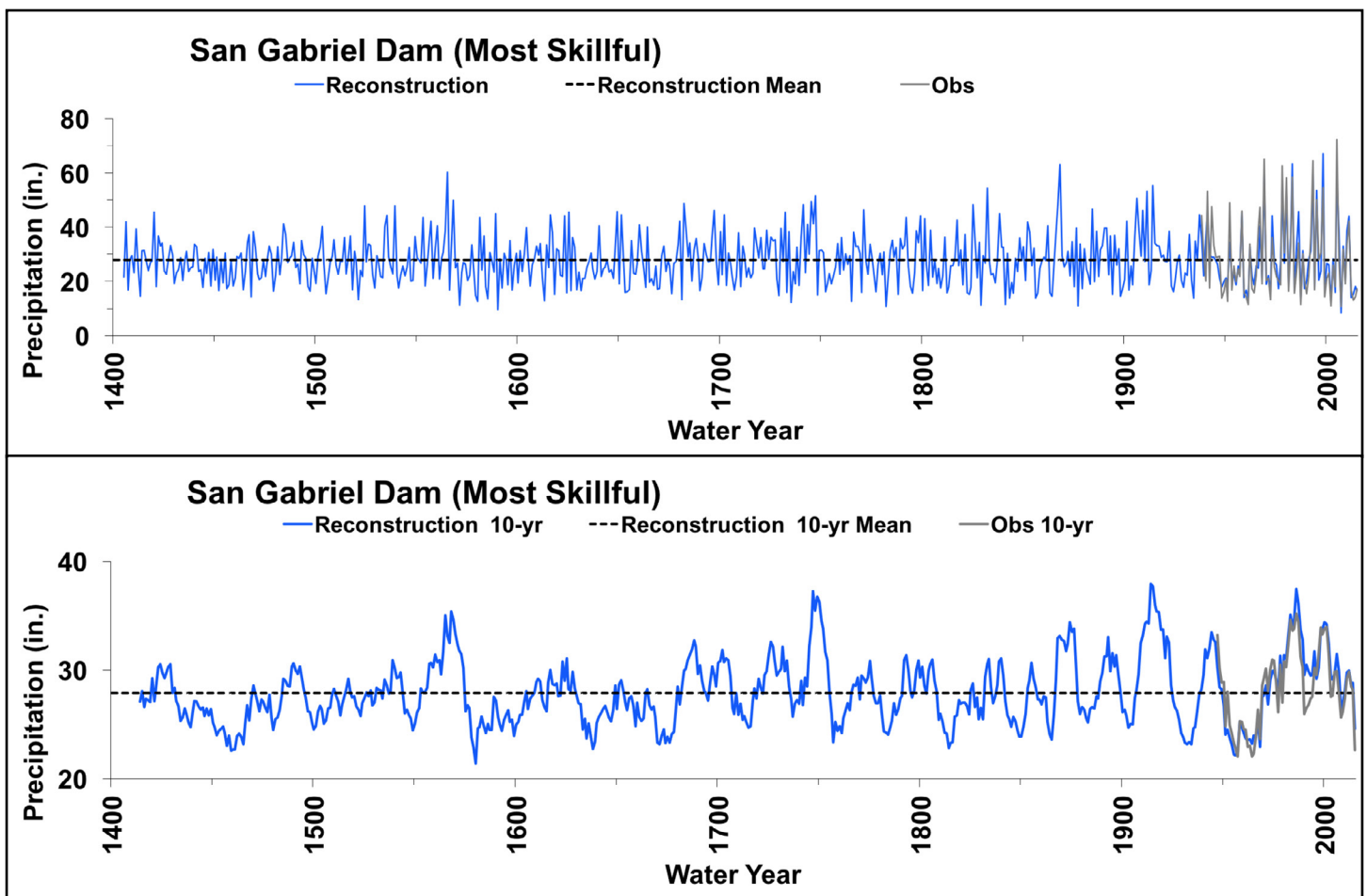
Figure 22. Time series graphs of the full San Gabriel precipitation reconstruction (blue line), with the observed record (gray line). The top graph shows the annual values and in the bottom graph, the reconstruction is smoothed using a 10-year moving average.

FAQ#4: I don't see a reconstruction for my basin of interest. Can I use a reconstruction for a nearby basin?

Yes, reconstructions for these gages are relevant for neighboring basins. Winter precipitation is a major component of water-year precipitation or streamflow in California. In winter, the moisture from frontal storms falls over a region that is larger than a single watershed. Because of this, the neighboring basins generally experience a similar climate, since climate is not constrained by watershed boundaries. If you are interested in a particular basin for which there isn't a reconstruction, the reconstruction from a nearby basin is fine to use.

4

Assessing observed droughts in a long-term context

The recent drought in California (2012-2016) was extremely severe, and the years 2012-2015 were the four driest consecutive years of statewide precipitation on record. Along with the recent drought, the three most severe multi-year statewide droughts were the six-year event of 1929-34, the two-year event of 1976-77 and the six-year event of 1987-92 (for more information, see http://www.water.ca.gov/waterconditions/docs/California_Signficant_Droughts_2015_small.pdf) (Figure 23).

Instrumental records of precipitation and streamflow document other significant droughts of the past 100 years, some less severe on an annual basis, but some longer-lasting than the recent drought. Other droughts were more severe than the recent drought, but occurred at a regional scale. For example, in southern California, a number of precipitation and streamflow gages indicate 4-year periods as dry as or even slightly drier than the 2012-2015 period.
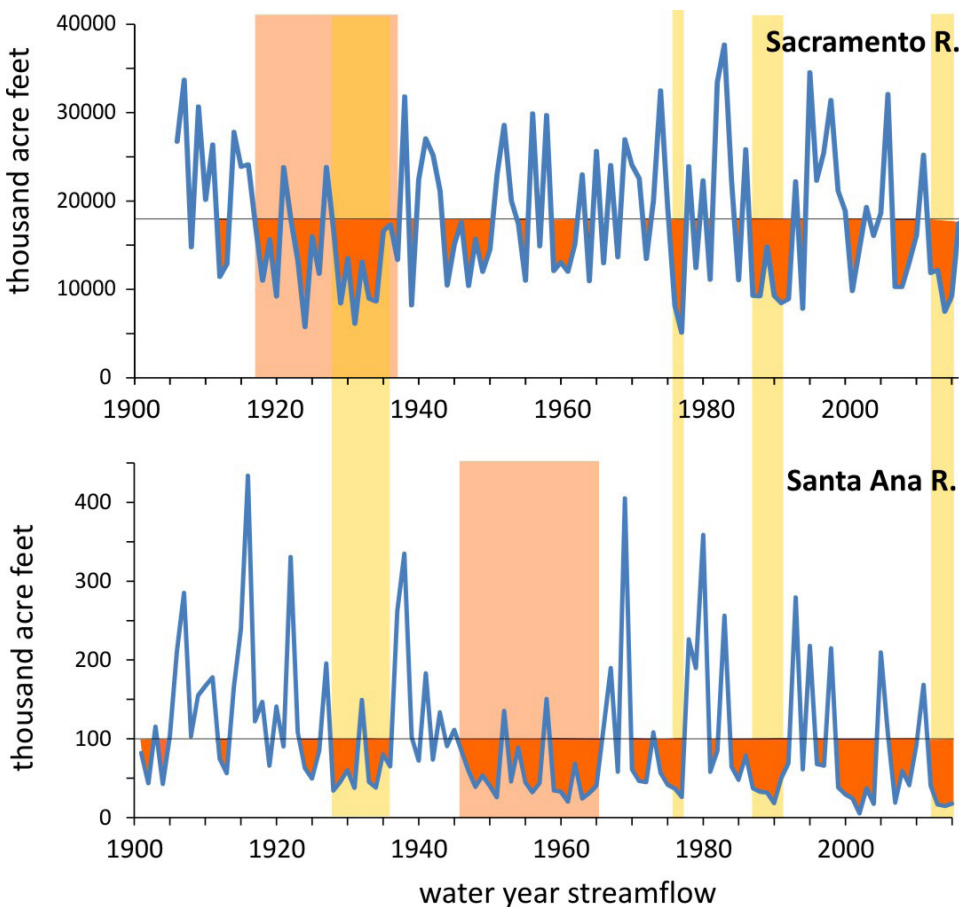

Figure 23. Sacramento, 1906-2015 (top) and Santa Ana, 1901-2015 (bottom) Rivers estimated natural water year streamflow, in thousand acre feet of flow. California state-wide droughts are indicated with transparent yellow bars. The worst period of drought in the two regions, 1920-30s in northern California, and the 1940s-50s in southern California droughts are highlighted with transparent orange bars.

These occurred in the late 1940s-early 1950s and in the late 1990s-early 2000s. This region's most severe and sustained period of drought occurred during the middle part of the century. Drought conditions persisted with brief breaks from the late 1940s into the 1960s, as shown for the Santa Ana River (Figure 23). In many southern California gages, the 10-year period from the mid-1950s to mid-1960s was the driest or second driest decade on record (Cuyamaca is shown as an example in Figure 24).

In contrast, in the Sacramento and San Joaquin River basins, the most persistent and severe drought conditions occurred in the 1920s and into the 1930s (Figure 23). In this region, the mid-century drought was much shorter than in southern California, with an earlier onset. After the 1920s-30s, the driest decade in the Sacramento River basin was 1985-1994, which was also one of the driest decades in the Kern River basin (Figure 24). In both of these basins, the decade from 2006-2015 was the third driest on record.
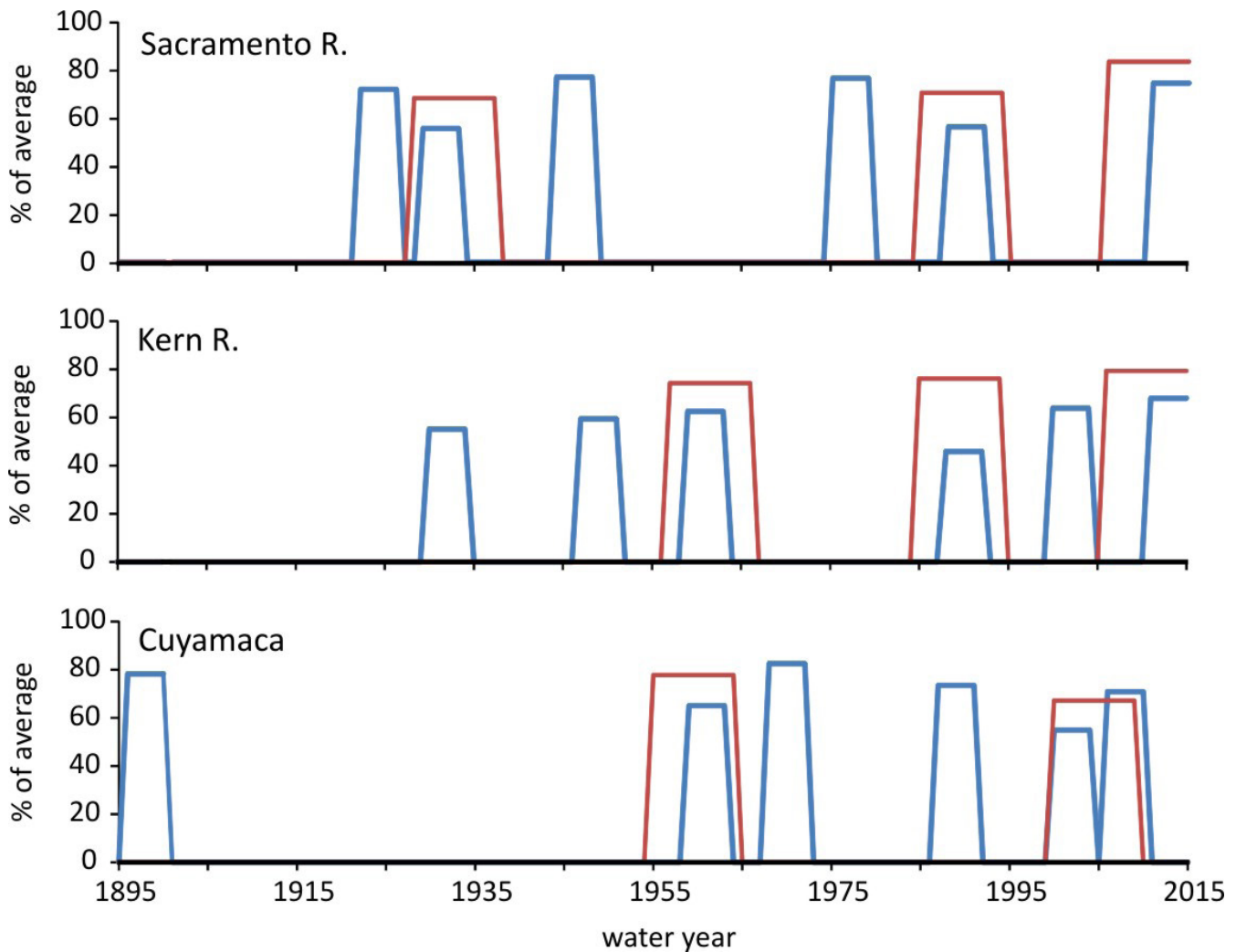

Figure 24. Driest five-year (blue line) and ten-year (red line) average periods (non-overlapping) in Sacramento and Kern River estimated natural streamflow and Cuyamaca precipitation records. Values are percentage of average over the five- or ten-year period. The six driest 5-year and two or three driest 10-year periods are shown. Start dates for records are: Sacramento River, 1906; Kern River, 1930; Cuyamaca, 1888.

HOW DO DROUGHTS OF THE LAST 120 YEARS COMPARE WITH DROUGHTS DOCUMENTED IN THE CENTURIES-LONG RECONSTRUCTIONS OF PRECIPITATION AND STREAMFLOW?

Extended records from tree rings document a wider range of drought variability than contained in the length-limited instrumental records. A reconstruction for Ojai water year precipitation extending back to 1400 provides a long-term context for assessing the short instrumental record. Figure 25a clearly shows droughts in the mid- to late-1400s and late 1500s to early 1600s to be more severe and persistent than any drought in the 20th-21st centuries.

If the 5-year averages for the full reconstruction are ranked, 2012-2016 comes in as the second driest period for Ojai, after 1841-1845. But if the averaging period is extended to 10 years, droughts in the late 1500s and mid-1400s are driest, followed by those in the 1920s-30s and 1940s-50s (Figure 26, top). The driest ranking multi-decadal periods are also in the 1400s and 1500s.
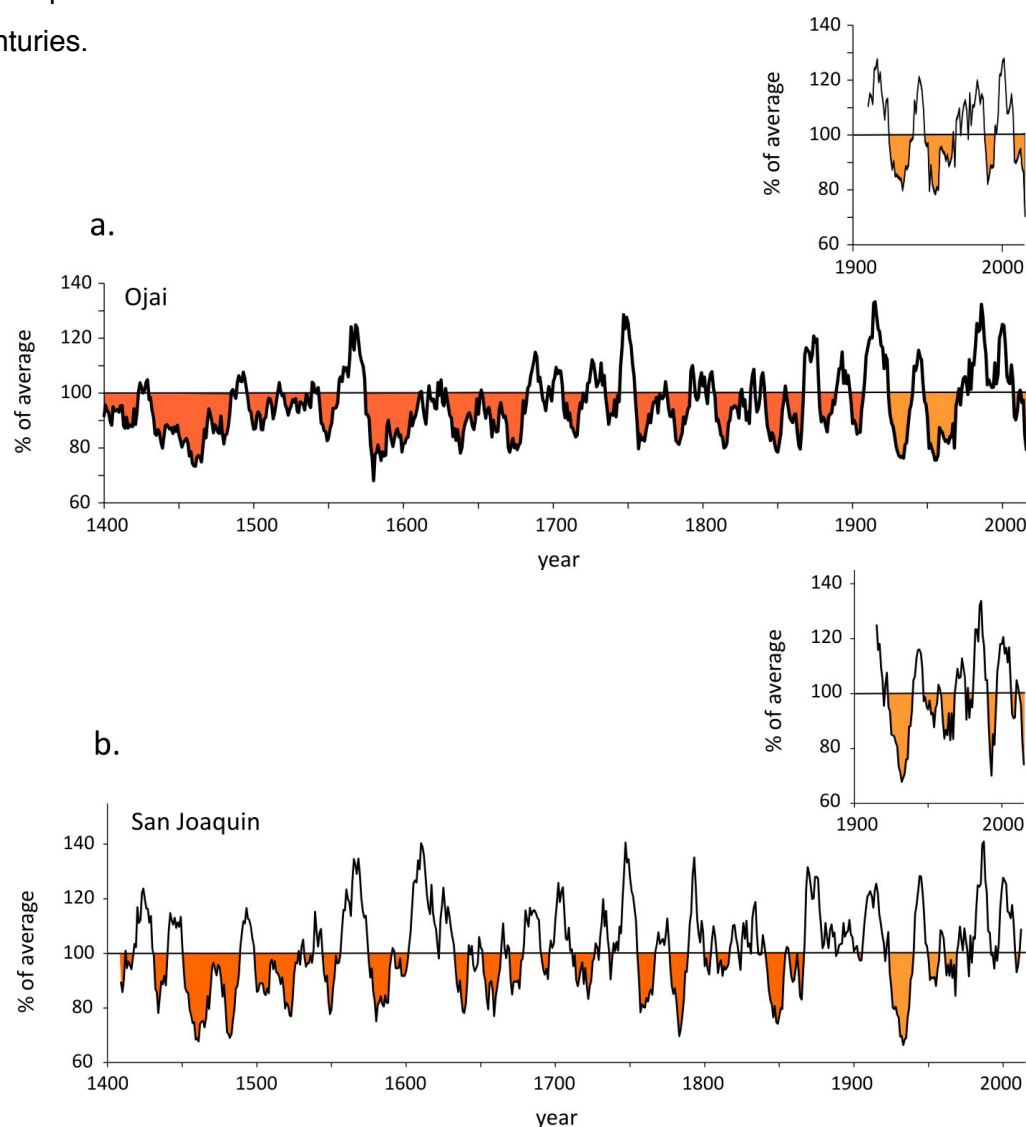

Figure 25. a. Ojai total water year precipitation. The top graph is the observed record, 1901-2015, and the graph below is the reconstruction, 1400-2016. Annual values are smoothed with a 10-year moving average. Units are in percent of average, based on the observed record average. b. The same as for part a, but for San Joaquin River water year streamflow. Top graph is natural flow record, 1906-2015; bottom is reconstructed flow, 1400-2012.

Similar assessments can be made for gages in other parts of California. In the case of the San Joaquin River reconstruction, the severity of the 1930s drought is outstanding in the context of the full reconstruction (Figure 25b), although the most persistent period of drought occurred in the second part of the 1400s. The 1930s drought encompasses both the driest 5- and 10-year periods, while the driest 20-year period falls in the mid-1400s (Figure 26, bottom).

Another way to assess 20th-21st century droughts relative to the longer record is to examine two dimensions, duration and average annual severity, together. Again, looking at the Ojai reconstruction, droughts in the period of instrumental record are clearly a subset of those that have occurred in past centuries (Figure 27, top). The extended record documents several droughts that are longer than have occurred in the instrumental period.
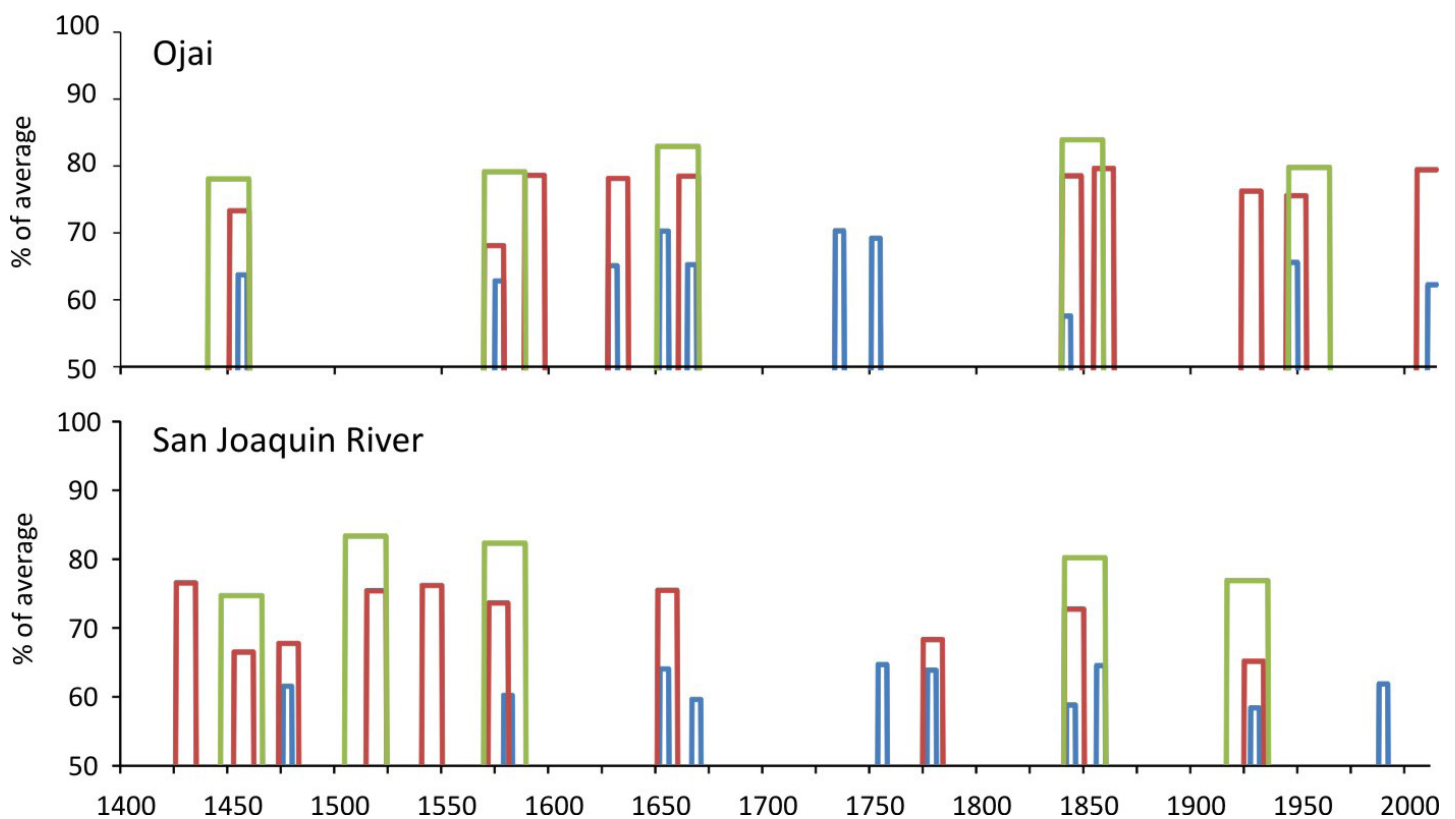

Figure 26. Driest five-year (blue line), ten-year (red line), and twenty-year (green line) average periods (non-overlapping) for Ojai annual precipitation (top) and San Joaquin (bottom), 1400-2016. Values are percent of average over the five- ten- or twenty-year period.

However, for 5-year droughts, the 2012-2016 drought has been the most severe on an average annual basis, and there have only been two 9-year events, both of which occurred in the instrumental period. For droughts of other durations, particularly six years and longer (except 9-year events), earlier droughts were more severe than those of the instrumental period. The San Joaquin River record shows much the same story (Figure 27, bottom). In this case, the 3-, 6- and 9-year instrumental droughts were the most severe for that length over the full record, but the reconstruction also documents the occurrence of 12- and 13-year droughts in the 1400s.

Figure 27. Ojai precipitation reconstruction (1400-2016) (top), and San Joaquin River flow reconstruction, 1400-2102 (bottom), with droughts plotted as duration versus average annual severity (percent of average). Droughts are defined as consecutive years below the instrumental record average. The red dots represent droughts occurring in the 20th or 21st century, for comparison with the full record.
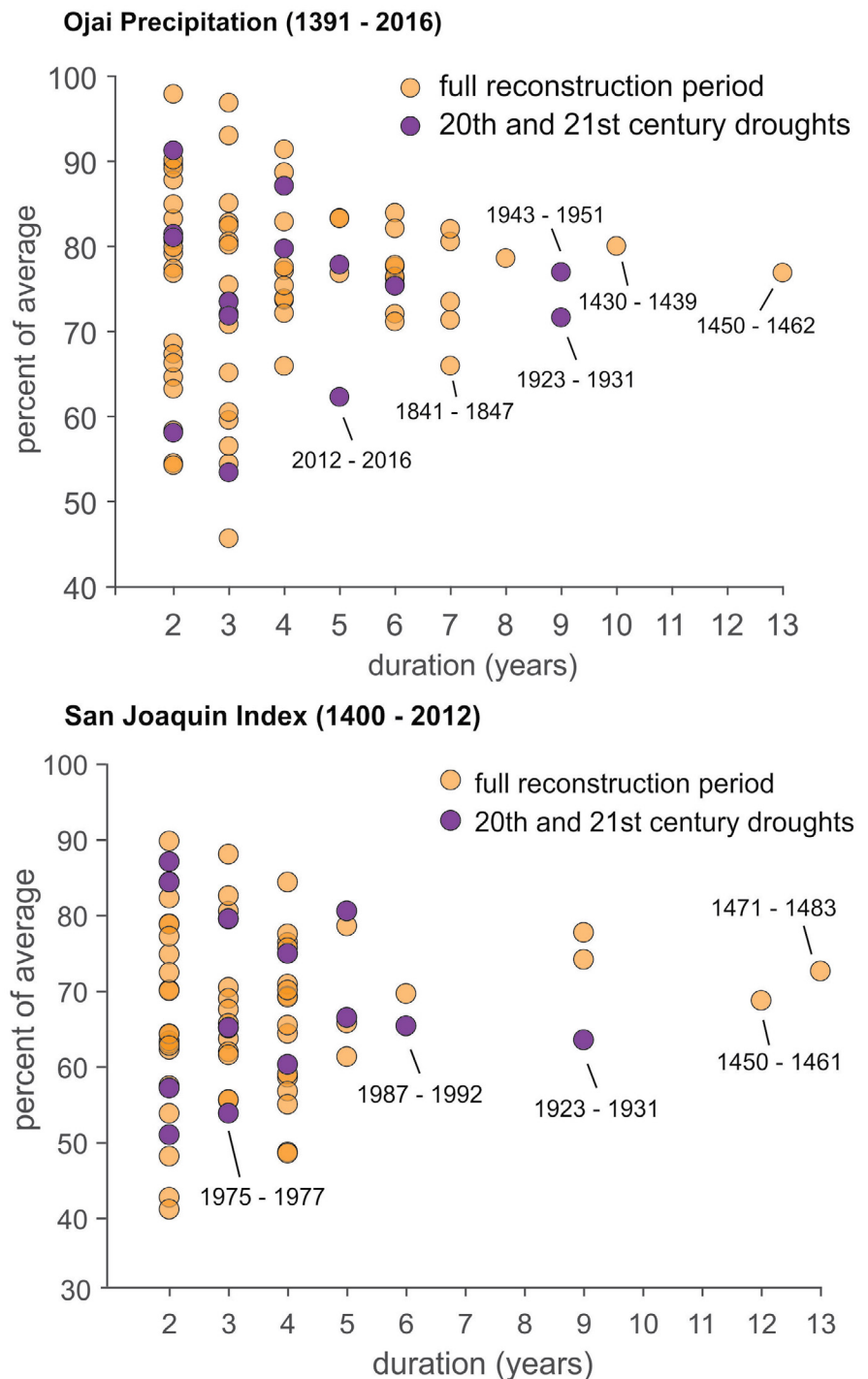
FAQ#5: Are the drought years independent of each other? If this is year 3 of a drought does it mean a higher probability of having a dry year 4 than otherwise?

Not entirely, and in the case of longer droughts, the likelihood of that drought persisting may increase because of certain feedbacks. Surface heating and dustiness, initially exacerbated by drought, can lead to feedbacks which further extend the duration of the drought. In addition, certain ocean/atmosphere conditions can promote persistence of drought conditions. However, these factors are not consistent enough allow a prediction of the probability of 3-year drought being followed by a fourth year.

5

Iconic droughts of the past

In California, the period that stands out in terms of overall dryness and drought duration over the past six centuries is a two-decade period from the 1440s to 1460s (Figure 28, top). In a number of the southern California reconstructions, these decades mark the driest (Lake Arrowhead, Arroyo Seco, and Ojai) or second driest (San Gabriel and Santa Ana River) 20-year period since 1400. The longest duration drought in southern California over the past six centuries also occurred during this interval of time (Figure 25a). Both the Arroyo Seco and Santa Ana streamflow reconstructions document 24 consecutive years of below average flow from 1442 to 1465. Moving north, the Kern River reconstructions indicates the 1440s-1460s period to be the second driest 20-year period, with 13 consecutive years of below average flow from 1450-1462. In the San Joaquin basin, one above average flow year in 1445 breaks this drought, but otherwise, the pattern of persistent drought is the same (Figure 28, top). Only in the Sacramento River basin is this drought less sustained, with a 4-year break near the beginning, from 1447-1450, but drought then persisted the next 11 years. These records suggest that statewide drought conditions likely existed from 1451 to 1461. There is a brief pause in drought conditions in most

reconstructions in the early 1460s, but drought conditions then return for a few more years before several years of wet conditions in 1466-67 break this period of persistent dryness.

In the set of longer, but less skillful reconstructions extending back to the 1100s, the 1440s-60s drought appears more moderate compared to an exceptional period of drought in the mid-1100s. This period of drought has long been recognized in the Upper Colorado River basin as the iconic medieval period drought, and it is evident in the reconstructions of drought in California as well. In this region, a 20-year interval centered in the 1140s is the driest two-decade period across all southern California reconstructions, as well as the Kern River reconstruction (Figure 28, bottom). Persistent low flow conditions are also documented in the San Joaquin and Sacramento River reconstructions, but this period is broken by a few above average years. In particular, the San Joaquin River reconstruction reflects more frequent breaks in the drought. The persistent dry period ends in 1159 at all gages, and conditions then become more variable.
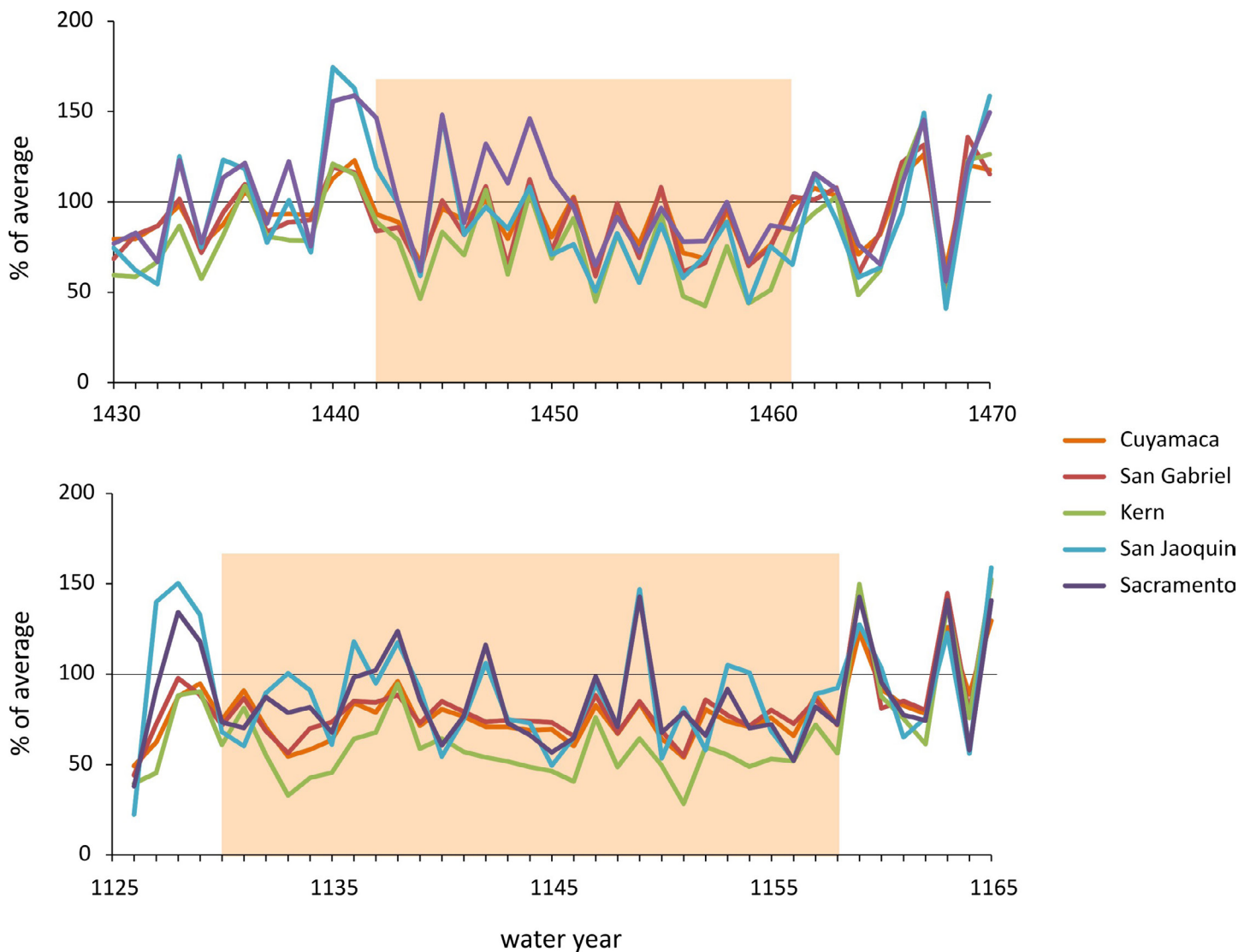
Figure 28. Reconstructed precipitation for Cuyamaca and San Gabriel, and reconstructed streamflow the Kern, San Joaquin, and Sacramento Rivers, in percent of the instrumental record average. The shaded box shows the severe drought period, 1442-1461 (top) and 1130-1158 (bottom). The horizontal line indicates 100% of average.

FAQ#6: Are there past droughts that were worse than what we're going to get with climate change?

The paleorecord identifies many long droughts, including some far longer than any we have experienced in the 20th and 21st centuries. However, there is no reason to expect that droughts as persistent as those in the past would not occur in the future. In addition, future droughts will occur under warmer conditions than in the past, intensifying the impacts of these droughts. Therefore, it is highly likely that with climate change we could experience droughts worse than those of the past.

6

Droughts across basins

Since the turn of the 21st century, drought conditions have plagued watersheds throughout the western US. As mentioned above, in California, a severe statewide drought occurred from 2012-2016. In the Upper Colorado River basin, drought conditions, as reflected by reservoir levels in Lake Mead, have been ongoing since 2000, with the 2000-2015 as the driest 16-year period in the instrumental record. Although this has been a west-wide period of drought, the severity of drought conditions has varied across northern and southern California and the Colorado River basin since 2000, with slight offsets in severity from year to year, and a few intermittent years of recovery (Figure 29).

Have there been periods in the past when severe and persistent drought was synchronous across the entire region – southern and northern California, and the Upper Colorado River basin – similar to, or even worse than the 2000-2016 period of drought?

An examination of reconstructions of streamflow for the Sacramento River and the Colorado River at Lees Ferry, and San Gabriel precipitation (to represent southern California) provides some insight on this question (Figure 30). Periods of drought (consecutive years of near to below average conditions; 110% or less) are evident across the three regions throughout the past six centuries, but most are limited to three or four years. Sets of three

Figure 29. Sacramento River and Colorado River natural flow with San Gabriel precipitation, 1990-2015. The horizontal line marks 100% of average for three records.
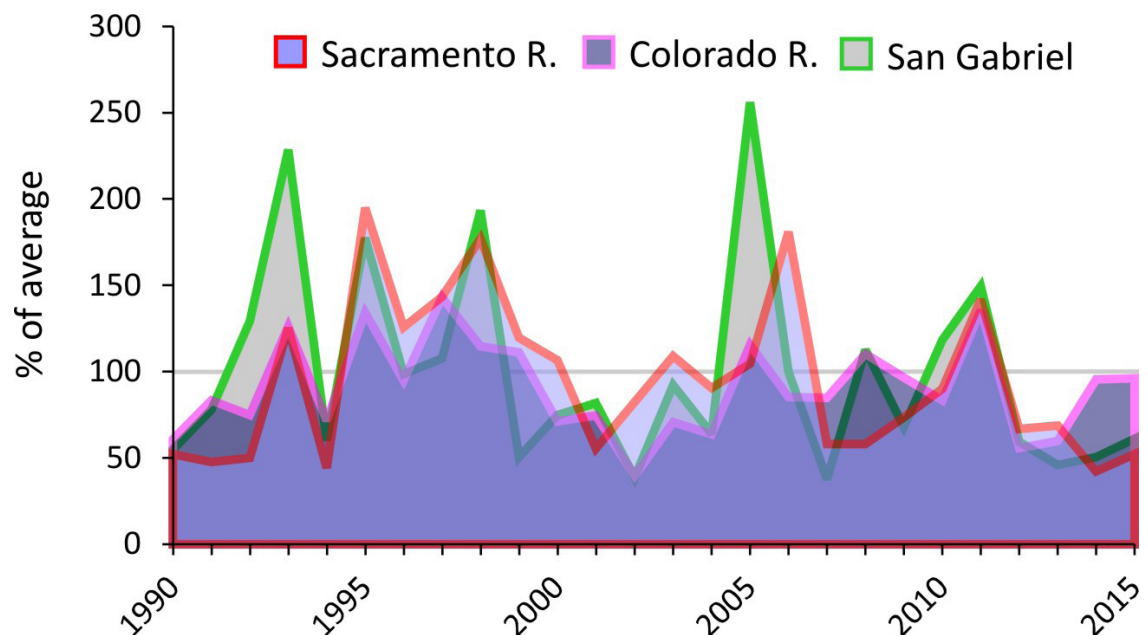
or more years with concurrent drought across three basins in which the average annual value is 75% of average or less have occurred approximately twice a century. However these region-wide events range from four events in the 18th century, to one event in the 20th century (the 15th century is incomplete) (Figure 30). While the majority of these widespread drought events last only three years, there are two nine-year events, 1452-1460 and 1775-1783. An 11-year period from 1451-1461 slightly exceeds the average annual threshold of 75%, but is notable for its length (the annual average value is 78%). Clearly, these widespread and persistent drought events are relatively rare, but they do occur periodically. While there have been only two cases of 9-year concurrent drought in about six hundred years, the statistical probability of one of these events occurring in the future is quite low, but not out of the question.
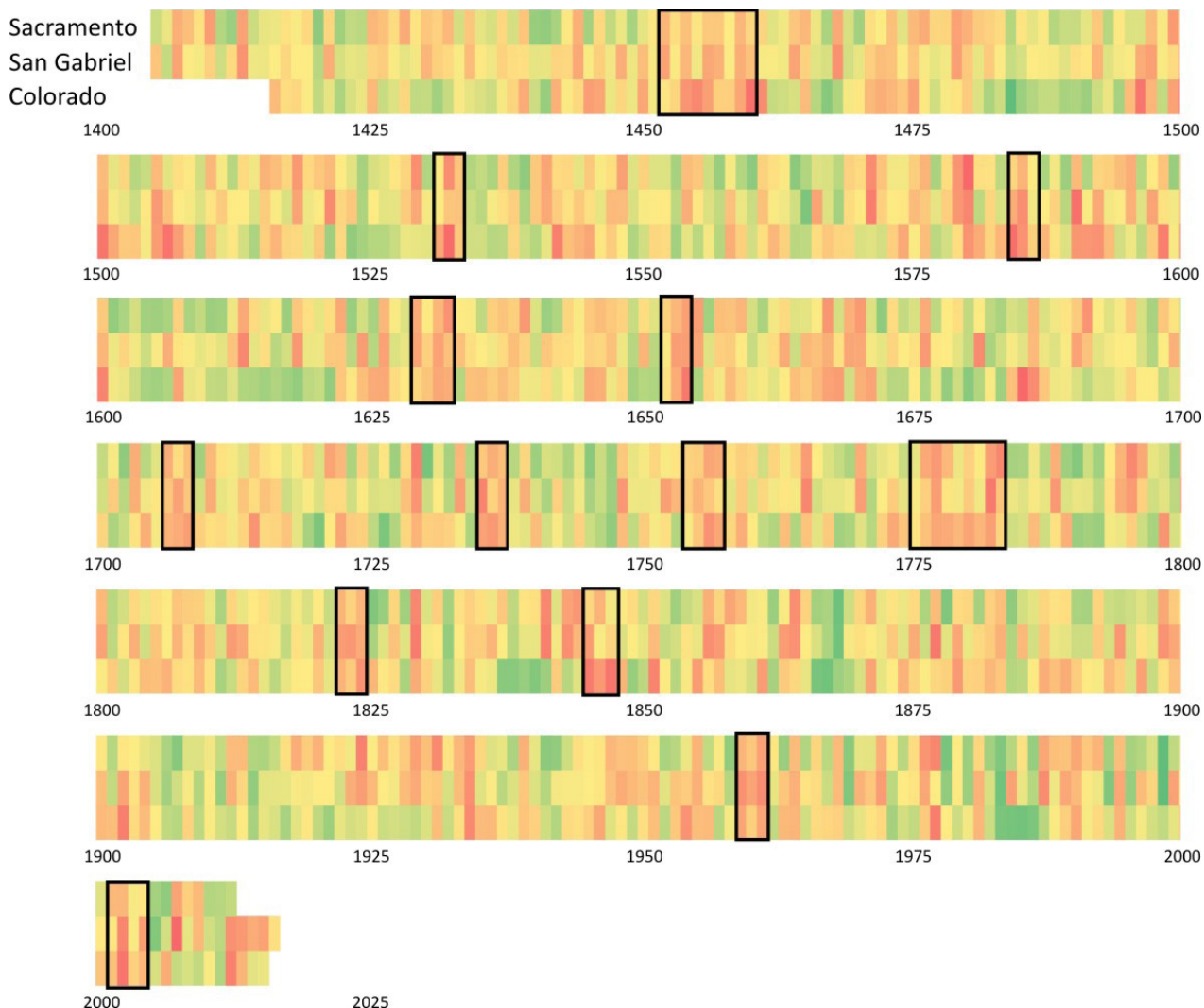

Figure 30. Annual values for the Sacramento River Index (1405-2012, top row in each set of horizontal bars), San Gabriel precipitation (1405-2016, middle row), and the Colorado River at Lees Ferry (1416-2015, bottom row) reconstructions. Plots are organized chronologically by century from top to bottom. Years are color coded, grading from wettest/highest flow (dark green) to driest/lowest flow (red). Sets of years in which values are 110% of average or less in all records, lasting three years or more, with an annual average value of 75% or less are shown with black outlines. The exception to this is the 11-year period, 1451-61, with average annual values of 78%.

7

Summary and Conclusions

Tree-ring reconstructions of California streamflow and precipitation, along with the Colorado River reconstruction, provide a basis for assessing the recent drought events in a long-term context. Information presented here suggests that in some cases, depending on how droughts are defined (i.e., a particular duration, or severity), instrumental period droughts may represent worst-case scenarios. Overall, however, these reconstructions clearly illustrate that the droughts of the instrumental period represent just a subset of the droughts that have occurred in the past, and that are likely to occur in the future.

Of particular note, the tree-ring based reconstructions document droughts that have exceeded the duration of the longest drought in the instrumental periods, in some cases, doubling or more the number of consecutive years of below average flow or precipitation. The longer droughts persist, the greater the impacts, as soils dry, vegetation dies, and aquifer levels drop. The longer drought duration documented in these extended records may provide some insights on potential impacts that future prolonged drought might entail.

What is the best way to use this information in planning for drought? The answer to this question will vary for each water provider, depending on the particular characteristics and underlying considerations of each agency. However, there are some general ways in which these kinds of data have been applied to water resource management and to the assessment of drought risk.

FAQ#7: Can the tree-ring based reconstructions of streamflow and precipitation be used to predict future drought in a probabilistic sense?

Reconstructions document the range of conditions that have occurred in the past during a time when the dominant external influence on climate – solar radiation variability due to Earth's orbit—has changed only slightly. Consequently, there is no reason to believe conditions that occurred in the past, including extended droughts, could not occur in the future, under natural climate conditions alone. However, while the reconstructions provide a guide to the range of conditions we should expect in the future, they cannot be used to predict the future. In addition, because today's climate is being impacted by humans in ways it wasn't in the past, the past is not an exact analogue for the future.

FAQ#8: Why don't we have drought frequency curves like we have flood frequency curves?

Flood frequency curves provide a recurrence interval (or exceedance probability) for any flood magnitude, based on a record of peak floods for a stream gage. Flood events are defined by a single metric, the annual peak flow. The recurrence intervals are prescribed by a uniform technique developed by a federally-appointed panel of hydrologists, statisticians and economists over several years, applied to nearly all flood series across the US since 1982. In contrast, droughts are often defined by several metrics, including duration, intensity, and spatial extent. The choice of metric depends on the user, along with the specific definition of drought (e.g., years below average). Because of the variety of ways to define and measure droughts, there is no uniform method for determining recurrence intervals. While it may be possible to calculate frequency curves for a particular metric (for example, drought duration), this would ignore the multiple dimensions of drought, and potentially lead to misleading conclusions.

Streamflow reconstructions are being used in the western US:

- To provide an awareness of a broader range of hydrologic variability than contained in the gage record
- As the basis for determining a drought "worst-case scenario"
- To test system reliability under a broader range of conditions by incorporating reconstruction data into water supply models
- When used in combination with climate change projections, to assess a range of plausible future scenarios
- To communicate risk or to aid in making recommendations

Several specific examples of applications of tree-ring reconstructions of streamflow to water resource management can be found in the TreeFlow website (http://www.treeflow.info/applications) and in some of the documents listed in the Resources section.

On a final note, climate of the past is unlikely to be an exact analogue for the future. However, the range of climatic and hydrologic variability that has occurred under natural conditions will continue in the future, along with the impacts of climate change. Planning for the future by considering the record of past droughts, while also acknowledging that future droughts will occur under warmer temperatures, may be a prudent strategy for water resource managers in southern California. We hope that you find these tree-ring based reconstructions of streamflow and precipitation of use in water management and drought planning applications.

8

Resources

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